The Wake Vortex Prediction and Monitoring System WSVBS Part I: Design

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The design of the Wake Vortex Prediction and Monitoring System WSVBS is described with all its components and their interaction. The WSVBS was developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways. The WSVBS supports dynamic adjustment of aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. The prediction tools employ a number of conservative aircraft parameter combinations that represent the medium and heavy aircraft weight categories. Safe aircraft separations correspond to times when the predicted safety areas associated with wake vortices generated by leading heavy aircraft cannot overlap the arrival flight corridor. A LIDAR monitors the correctness of WSVBS predictions in the most critical regions at low altitude.

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INTRODUCTION

Aircraft trailing vortices may pose a potential risk to following aircraft. The empirically motivated wake vortex separation standards that were first introduced in the 1970s still apply. The current aircraft separations standards limit the capacity of congested airports in a rapidly growing aeronautical environment. Capacity limitations are especially drastic and disagreeable at airports with two closely-spaced parallel runways (CSPR) like Frankfurt Airport (Germany) where the potential transport of wakes from one runway to the adjacent one by crosswinds impedes an efficient use of both runways.

The most rapid growth scenario within a EUROCONTROL study [EUROCONTROL, 2004] indicates that in the year 2025 sixty European airports could be congested and up to 3.7 million flights per year could not be accommodated. The introduction of a wake-vortex advisory system could achieve estimated annual savings of direct operating costs of US $ 15 million per year at congested airports that have a closely-spaced parallel runway configuration [Hemm et al., 1999]. This estimate accounts only for cost avoidance based on reductions in arrival delays. Savings due to reduced departure delays, value of passenger time, additional airline revenue, avoidance of runway or airport construction and airline relocation are not considered. A survey of wake-vortex advisory systems and procedural modifications meant to increase airport capacity is available in [Elsenaar, 2006].

The Deutsche Zentrum für Luft- und Raumfahrt (DLR) has developed the Wake Vortex Prediction and Monitoring System (Wirbel-Schleppen-Vorhersage- und Beobachtungs-System WSVBS [Gerz et al., 2005]) to tactically increase airport capacity for approach and landing. The WSVBS shall support dynamic adjustment of aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. The system is particularly adapted to the closely spaced parallel runway system of Frankfurt airport. For this purpose it predicts wake vortex transport and decay and determines the resulting safety areas along the glide slope from final approach fix to threshold. The elements of the WSVBS are generic and can be adjusted to other runway systems and airport locations.

This paper describes the design of the WSVBS with all its components and their interaction. The experimental integration of the WSVBS into air traffic control automation systems and its promising performance during a three-month measurement campaign at Frankfurt Airport are described in Part II of this paper. Precursor versions of these papers have been presented at the CEAS Conference 2007 [Gerz et al., 2007; Holzäpfel et al., 2007].

SYSTEM OVERVIEW

Figure 1 delineates the components of the WSVBS and their interplay. The bottleneck of runway systems occurs near the ground where stalling or rebounding wake vortices may not descend below the arrival flight corridor. Therefore, the best wake prediction performance is required when wakes are in close proximity to the ground. The WSVBS incorporates measurements of meteorological conditions with a SODAR/RASS system and an ultra sonic anemometer (USA) to enhance the prediction of wake vortex behavior near the ground. Because it is not possible to cover the whole glide slope with such instrumentation the meteorological conditions in the remaining area are predicted with a numerical weather prediction system (NOWVIV) leading to predictions of wake position and strength with increased uncertainty bounds. Based on glide path adherence statistics (FLIP) the probabilistic wake vortex model P2P predicts upper and lower bounds for position and strength of vortices generated by heavy aircraft. These bounds are expanded by a safety area around a vortex that must be avoided by follower aircraft for safe and undisturbed flight (SHAPe). The instant these safety areas do not overlap with the arrival flight corridor defines safe temporal aircraft separations. These temporal separations are translated into dynamic separations based on established procedures by the DLR arrival manager (AMAN). The LIDAR monitors the correctness of WSVBS wake vortex predictions in the most critical gates associated

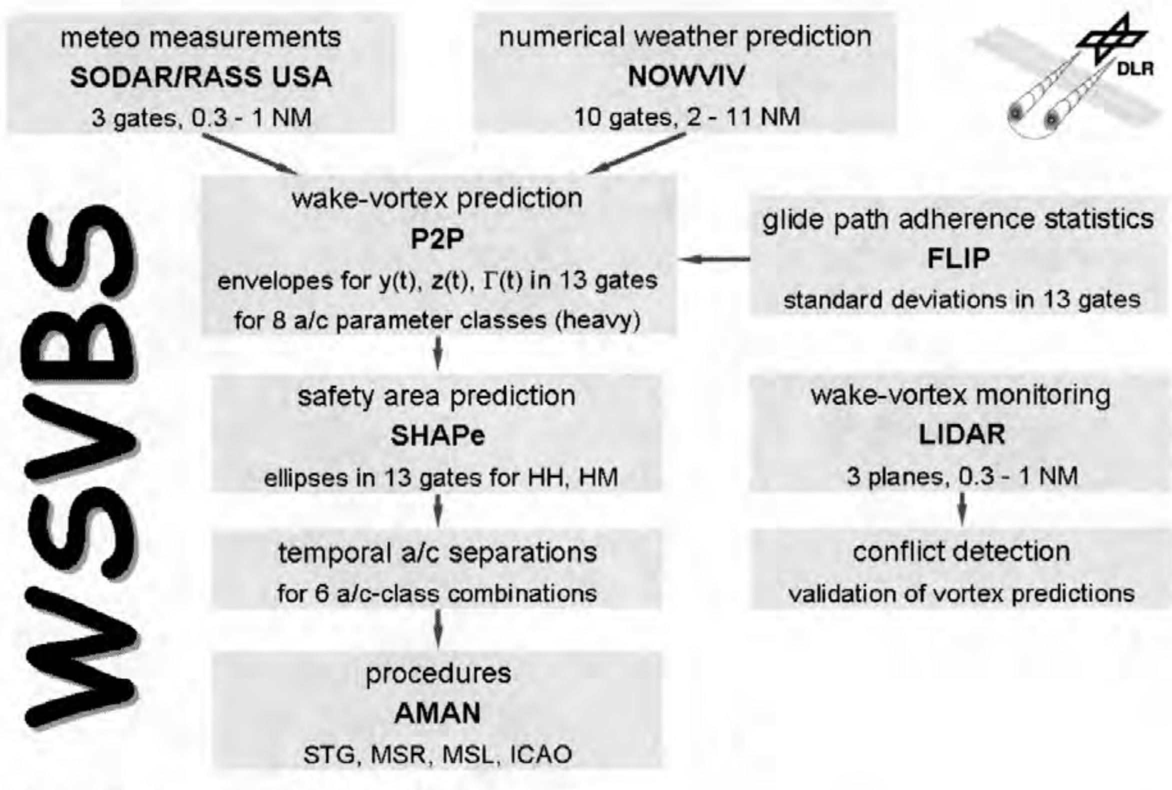

Figure 1. Flowchart of the WSVBS.

with the low altitude portions of the arrival corridor. The components of the WSVBS will be described in detail later, together with their respective references.

RELATED WAKE VORTEX ADVISORY SYSTEMS

The two wake vortex advisory systems that were most influential for the development of the WSVBS are briefly introduced in this section. NASA has been developing the Aircraft Vortex Spacing System (AVOSS) [Hinton et al., 2000] to produce weather dependent, dynamic wake vortex spacing criteria. The AVOSS concept provides for several similar components as those of the WSVBS described in the previous section. In a real-time field demonstration during July 2000 at the Dallas Ft. Worth International Airport, functional elements for meteorological measurements, glide path adherence statistics, wake-vortex prediction, and wake-vortex monitoring (cf. Figure 1) were applied to a single runway system [Rutishauser and O'Connor, 2001]. An increase of runway throughput of 6% was predicted, where less than 1% of the predictions did not yet safely represent the observed wake behavior.

The DFS Deutsche Flugsicherung GmbH has developed the Wake Vortex Warning System (WVWS) [Gurke and Lafferton, 1997] to allow for the suspension of wake vortex separation between subsequent aircraft approaching the closely-spaced parallel runways 25 at Frankfurt airport during favorable meteorological conditions. Based on wind and turbulence measurements of a 15 m anemometer array, the WVWS predicts whether or not wake vortices may reach the parallel runway in ground proximity. As described in Part II of this paper the landing procedures developed for the WVWS were adopted by the WSVBS.

Later the DFS established the so-called glide path extension of the WVWS, which employs a wind-temperature radar with a radio acoustic sounding system (WTR/RASS) to measure wind and temperature up to 5000 ft above ground level [Konopka and Fischer, 2005]. The limited fraction of time when safe approaches with reduced wake turbulence separation can be guaranteed prevents the operational utilization of the system.

A survey on further wake-vortex advisory systems and procedural modifications meant to increase airport capacity is available in [Elsenaar, 2006].

TOPOLOGY

The WSBVS concept requires that all aircraft are established on the glide slope at the final approach fix (FAF), which is situated 11 nmi before touchdown. For each runway, wake-vortex evolution is predicted within 13 distinct planes, termed gates, perpendicular to the final approach flight path. In ground proximity the nominal gate separation of 1 nmi is reduced to 1/3 nmi to properly resolve the interaction of wake vortices with the ground. Table 1 lists the gates' altitudes and distances from the touchdown zone (TDZ). Figure 2 delineates the parallel runway system with the employed geodetic coordinate system and some of the gates near the ground. The parallel runways and consequently also the gate centers are laterally spaced by 518 m and axially displaced by 226.5 m.

SYSTEM COMPONENTS

The different system components will be adjusted to produce consistent probability levels such that the WSVBS will meet accepted risk probabilities as a whole. Since a comprehensive risk assessment of the WSVBS is still pending, we currently employ 95.4% probabilities (two

Table 1. Gate Centre Positions Along Glide Path in Geodetic Coordinates

gate No	x_{gate} [nmi]	x_{gate} [m]	z_{gate} [m]
1	-11	-20372	-1077
2	-10	-18520	-979
3	-9	-16668	-880
4	-8	-14816	-781
5	-7	-12964	-683
6	-6	-11112	-584
7	-5	-9260	-486
8	-4	-7408	-387
9	-3	-5556	-289
10	-2	-3704	-191
11	-1	-1852	-94
12	-2/3	-1235	-61
13	-1/3	-617	-29

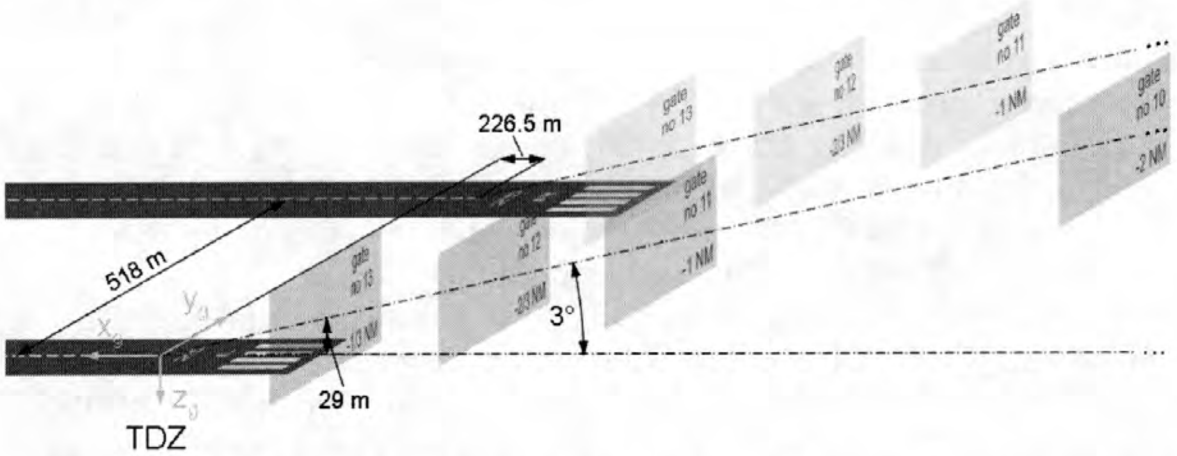

Figure 2. Zoom on gate topology for Frankfurt's closely-spaced parallel runway system.

standard deviations, 2σ, for Gaussian distributions) as a basis for the probabilistic components of the WSVBS. The following sections describe the components delineated in the flowchart in Figure 1 in detail.

Meteorological Data

For prediction of wake-vortex behavior along the final approach path meteorological conditions with good accuracy must be provided for the relevant airspace with a forecast horizon of 1 hour. A combination of measurements (employing the persistence assumption [Frech and Holzäpfel, 2008]) and numerical weather predictions provides for the required temporal and spatial coverage.

Instrumentation. For the three lowest gates at 1/3, 2/3, and 1 nmi from the TDZ a METEK Sodar with a RASS extension provides 10-minute averages of vertical profiles of the three wind components, the vertical fluctuation velocity, and virtual temperature with a vertical resolution of 20 m. The Sodar/RASS system is complemented by an ultrasonic anemometer (USA) mounted on a 10 m mast. Eddy dissipation rate (EDR) profiles are derived from the vertical fluctuation velocity and the vertical wind gradient employing a simplified budget equation [Frech, 2004]. A spectral analysis of the longitudinal wind velocity measured by the sonic anemometer is used to estimate EDR by fitting the -5/3 slope in the inertial subrange of the velocity frequency spectrum.

Numerical Weather Prediction. The non-hydrostatic mesoscale weather forecast model system NOWVIV (NOwcasting Wake Vortex Impact Variables) is used to predict meteorological parameters in the area that is not covered by measurements (the more remote 10 gates from 2 to 11 nmi). NOWVIV has been successfully employed for predictions of wake vortex environmental parameters in the field campaigns WakeOP 2001 [Holzäpfel and Robins, 2004] and WakeTOUL 2002 [Holzäpfel, 2006] of the Wirbelschleppe and C-Wake projects, respectively. It has also been successfully employed in the first flight test campaign 2003 of AWIATOR [Holzäpfel, 2006], and in the measurement campaign at Frankfurt airport accomplished in fall 2004 [Holzäpfel and Steen, 2007; Frech and Holzäpfel, 2008]. Detailed descriptions of NOWVIV and its nowcasting performance are available in [Frech et al., 2007; Gerz et al., 2005].

Within the forecast system NOWVIV, the mesoscale model MM5 [Grell et al., 2000] predicts the meteorological conditions for the Frankfurt terminal area in two nested domains with sizes of about 250 x 250 km^2 and about 90 x 90 km^2 centered on Frankfurt airport with grid distances of 6.3 km and 2.1 km, respectively. Sixty vertical levels are employed such that in the altitude range of interest (z < 1100 m above ground) 26 levels yield a vertical resolution varying between 8 m and 50 m.

Initial and boundary data of NOWVIV are taken from the operational weather prediction model LM (Local Model, [Doms and Schaettler, 1999]) of DWD (German Weather Service). The LM data allow for the best possible initialization and subsequent forcing of NOWVIV, since actual observations (radio soundings, AMDAR (Aircraft Meteorological Data Relay), satellite data, surface observations, etc.) are assimilated into the LM model predictions. Detailed topography, land use and soil type data for the Frankfurt area are also employed.

NOWVIV runs twice a day (at 00 and 12 UTC) on a dedicated Linux cluster at University of Stuttgart. Profiles of meteorological data are extracted at gates 1 through 10 with an output frequency of 10 minutes. The meteorological quantities are the three wind components, air density, virtual potential temperature, turbulent kinetic energy, eddy dissipation rate (EDR), and pressure.

Figure 3 shows the correspondence of measured (SODAR) and predicted (NOWVIV) key meteorological quantities for wake vortex

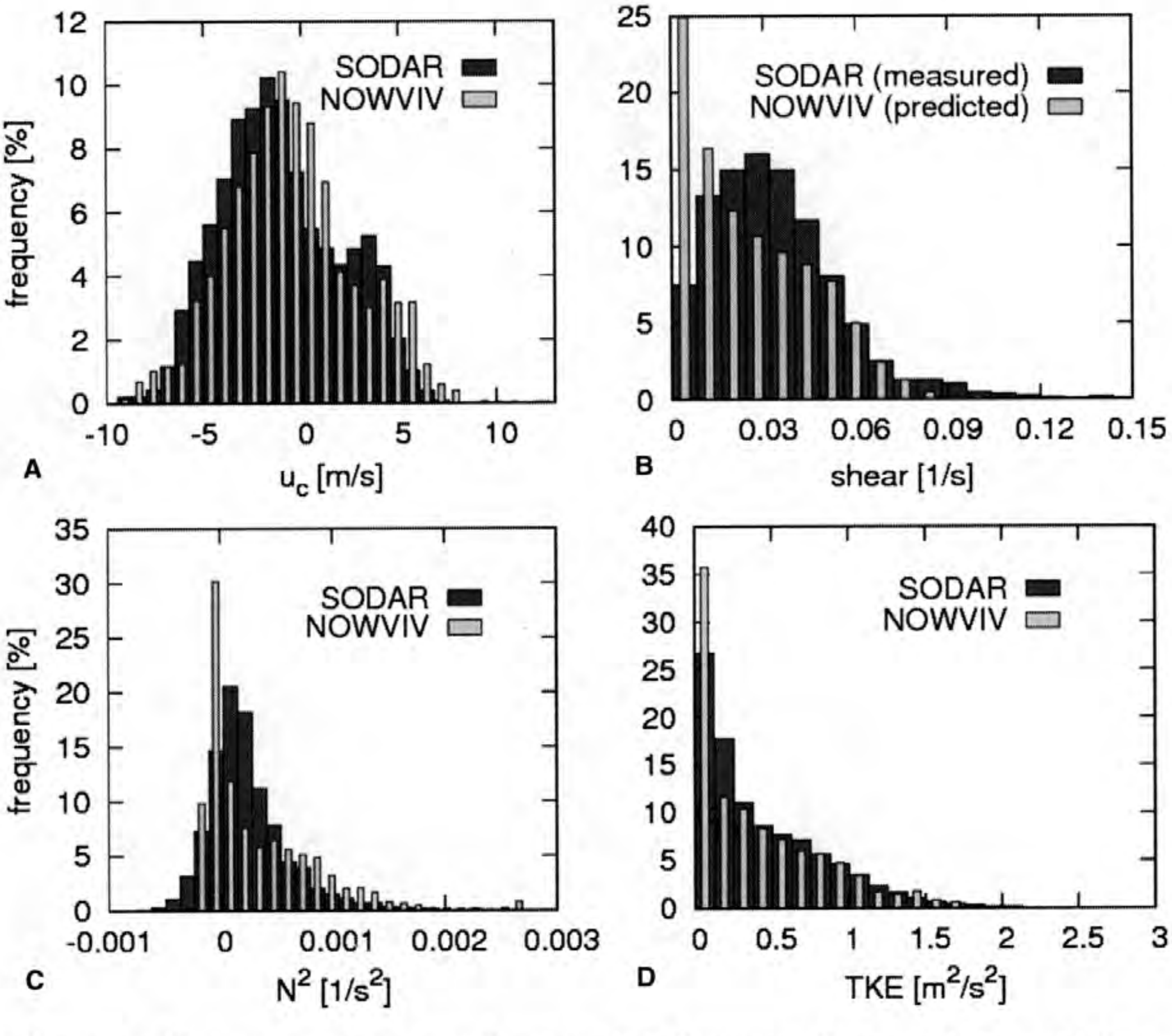

Figure 3. Histograms of measured and predicted crosswind (a), wind shear (b), temperature stratification (c), and turbulent kinetic energy (d) at a height of 100 m above ground for a 40-day measurement campaign at Frankfurt airport [Frech et al., 2007].

prediction collected during a 40 days measurement campaign conducted at Frankfurt airport in 2004 [Frech et al., 2007].

Integration of Meteorological Data. For approaches, the largest probability of encountering wake vortices prevails at altitudes below 300 ft [Critchley and Foot, 1991; Holzäpfel et al., 2009; Elsenaar, 2006]. There stalling or rebounding vortices may not clear the flight corridor vertically and weak crosswinds may be compensated by vortex-induced lateral transport, which may prevent the vortices from exiting the flight corridor laterally. Since vortex decay close to the ground is almost insensitive to meteorological conditions [Holzäpfel and Steen, 2007] the principal mechanism that may allow for reduced aircraft separations is lateral transport of wake vortices by crosswind.

Figure 4 shows that the best wake-vortex prediction performance for lateral transport is achieved employing SODAR wind measurement data. Only if it is assumed that the measured wind would persist for over 70 min (lead time), would the lateral vortex transport predicted with NOWVIV input yield superior results. In ground proximity, vertical transport and vortex decay is largely independent from meteorological conditions. Consequently, the average deviations between measured and predicted vertical transport and vortex

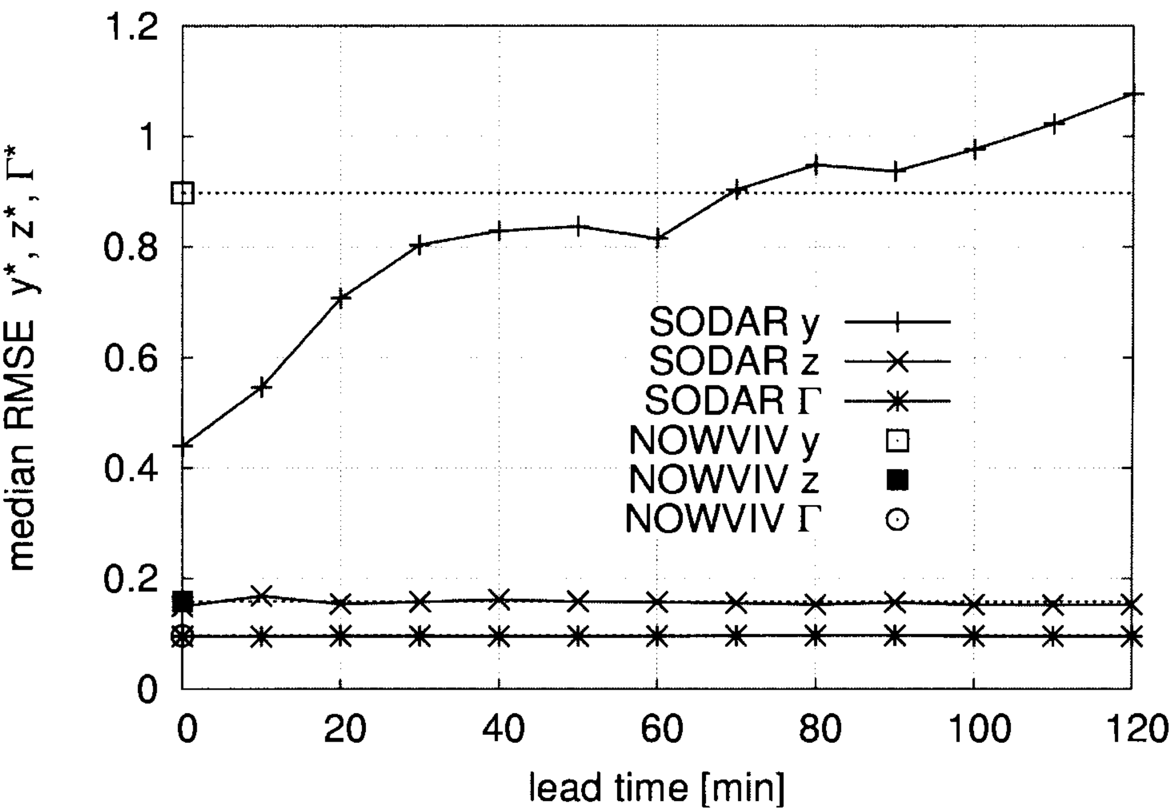

Figure 4. Median of normalized root-mean square deviations between measured and predicted lateral position, y*, vertical position, z*, and circulation, Γ*, as a function of the source of meteorological data and lead time.

decay are also almost independent from the source of the meteorological input data and the lead time.

Because it is not feasible to cover the complete final approach path with instrumentation we employ SODAR/RASS data for wake prediction in the bottleneck region at low altitudes (gates 11 – 13). For the less critical areas aloft, we use NOWVIV data, which yields lesser but still acceptable wake prediction characteristics.

Approach Corridor Dimensions

For the definition of approach corridor dimensions we employ the glide path adherence statistics of the FLIP study [Frauenkron et al., 2001], an investigation of the navigational performance of ILS (Instrument Landing System) approaches at Frankfurt airport. FLIP provides statistics of 35,691 tracks of precision approaches on Frankfurt ILS of runways 25L/R. It does not differentiate between manual and automatic approaches. The study indicates that the measured flight path deviations are much smaller than specified by ICAO localizer and glide slope tolerances. The employed corridor dimensions decrease monotonically when approaching the runways and are kept constant within a distance of 2 nmi from TDZ.

The approach corridors in the different gates consist of ellipses (see Figure 5). Vertical and horizontal semi axes of these ellipses correspond to two standard deviations derived from glide path adherence statistics, respectively. For Gaussian distributions two standard deviations (2σ) correspond to a probability of 95.4% that an aircraft does not leave the corridor in one dimension (either laterally or vertically). For ellipsoidal corridors this probability reduces to 86.5% assuming statistical independence of lateral and vertical positions.

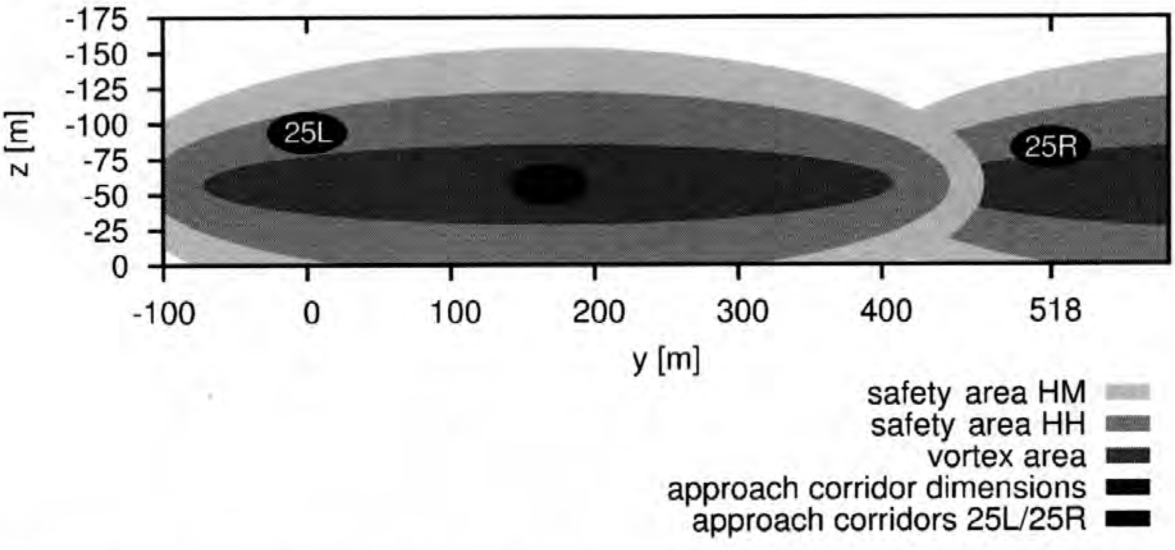

Figure 5. Ellipses denoting approach corridor dimensions, vortex areas, and safety areas in gate 11 for a vortex age of 100 s.

Representation of Aircraft Weight Classes

In principle, the WSVBS could predict conservative separations for individual aircraft pairings provided that the approaching aircraft types are known. However, in order to keep the system as simple as possible and, thus, to minimize additional workload for controllers, the WSVBS only considers aircraft weight class combinations. For Frankfurt airport the relevant combinations are heavy followed by heavy (HH) and heavy followed by medium (HM).

To conservatively represent generator aircraft parameters of the heavy weight category boundary curves for a representative compilation of parameters of existing aircraft as function of the maximum take-off weight (MTOW) (see solid lines in Figure 6) are established. For the individual aircraft the circulation of the generated wake vortices is calculated according to

$$\Gamma_0 = \frac{M \cdot g}{\rho(\pi/4)BV} \tag{1}$$

where M is the maximum landing weight (MLW), ρ is the air density of the standard atmosphere at sea level, B is the wing span, and V the final approach speed. Note that Figure 6 employs MTOW to characterize the various aircraft types because ICAO weight classes are based on MTOW. Nevertheless, the plotted and used circulation values are derived from MLW.

Figure 6 and Table 2 illustrate the way initial circulations, wing spans, and approach speeds are combined at the weight class

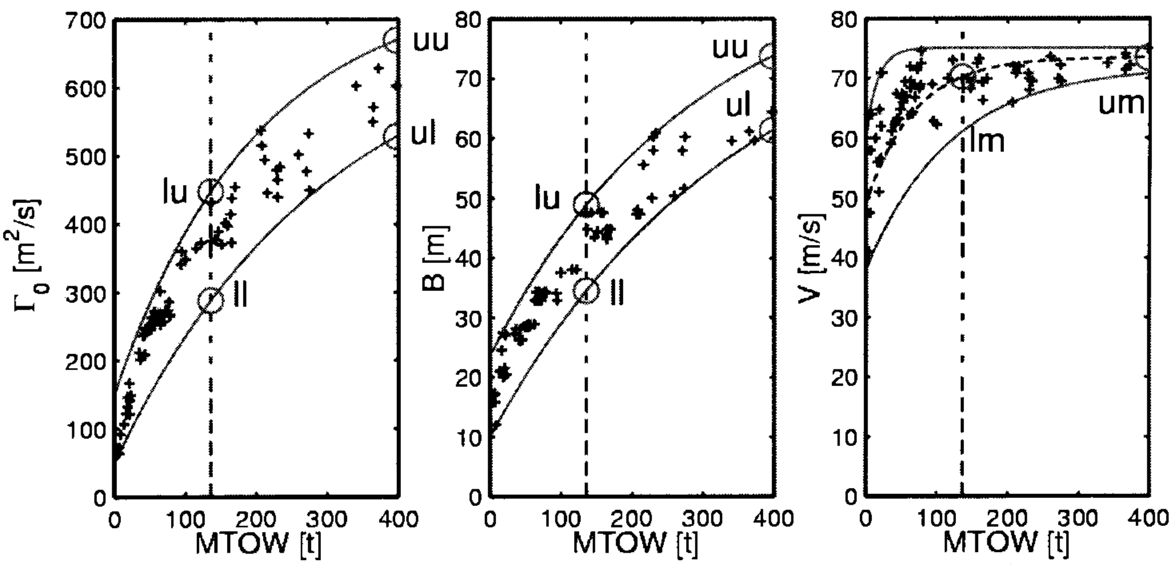

Figure 6. Initial circulation, Γ_0, wing span, B, and flight speed, V, for final approach as function of maximum take-off weight, MTOW, for 73 aircraft types. Solid lines border aircraft parameters, circles denote the parameters which are combined to represent the aircraft weight class heavy.

Table 2. Aircraft Parameter Combinations for Initial Circulation, Γ_0, Vortex Separation, b_0, and Flight Speed, V, Which Represent the Aircraft Weight Class Heavy and Resulting Characteristic Time Scales and Initial Descent Speeds (maxima and minima in bold)

parameter comb.	Γ_0 [m²/s]	b_0 [m]	V [m/s]	char. time scale t_0 [s]	desc. speed w_0 [m/s]
$\Gamma_{0uu}\ b_{0uu}$	669.2	57.9	73.5	31.5	1.84
$\Gamma_{0uu}\ b_{0ul}$	669.2	48.2	73.5	21.8	2.21
$\Gamma_{0ul}\ b_{0uu}$	528.5	57.9	73.5	**39.9**	1.45
$\Gamma_{0ul}\ b_{0ul}$	528.5	48.2	73.5	27.6	1.75
$\Gamma_{0lu}\ b_{0lu}$	448.1	38.4	70.3	20.7	1.86
$\Gamma_{0lu}\ b_{0ll}$	448.1	27.1	70.3	**10.3**	**2.63**
$\Gamma_{0ll}\ b_{0lu}$	288.2	38.4	70.3	32.1	**1.19**
$\Gamma_{0ll}\ b_{0ll}$	288.2	27.1	70.3	16.0	1.69

boundaries. In Table 2 $b_0 = \pi/4\ B$ corresponds to the vortex separation for an elliptically loaded wing. The B747-400 with a MTOW of 397 t is chosen as upper limit of the heavy weight category. Table 2 lists the 8 resulting parameter combinations that conservatively represent all possible generator aircraft within the heavy weight category. In Figure 6 and Table 2 the first u (l) denotes the upper (lower) bound of the weight class and the second u (l) upper (lower) fits at a weight class boundary. The resulting wide variations of initial vortex descent speed, w_0, and wake vortex time scales, $t_0 = w_0/b_0$, (variations by almost a factor of four) that are employed for any approaching aircraft indicate one of the conservative margins of the WSVBS.

Wake-Vortex Prediction

Wake-vortex prediction is conducted with the Probabilistic Two-Phase wake-vortex decay model (P2P), which is described in detail in [Holzäpfel, 2003]. Applications, assessments and further developments are reported in [Frech and Holzäpfel, 2008; Holzäpfel and Robins, 2004; Holzäpfel, 2006; Holzäpfel and Steen, 2007]. P2P considers all effects of the leading order impact parameters: aircraft configuration (span, weight, velocity, and trajectory), wind (cross and head components), wind shear, turbulence, temperature stratification, and ground proximity. P2P has been validated against data of over 10,000 cases gathered in two US and six European measurement campaigns (parts of this work have been documented in the above last four references).

Precise deterministic wake vortex predictions are not feasible operationally. Primarily, it is the nature of atmospheric turbulence that deforms and transports the vortices in a stochastic way and leads to considerable spatiotemporal variations of vortex position and strength. Moreover, the variability of environmental conditions must be taken into account. Therefore, the output of P2P consists of confidence intervals for vortex position and strength (see solid lines in Figure 7). The measured (symbols) and predicted (dashed and dotted lines) evolution of vertical (top left) and lateral (top right) wake vortex trajectories in Figure 7 illustrate asymmetric vortex rebound characteristics caused by crosswind in ground proximity [Holzäpfel and Steen, 2007].

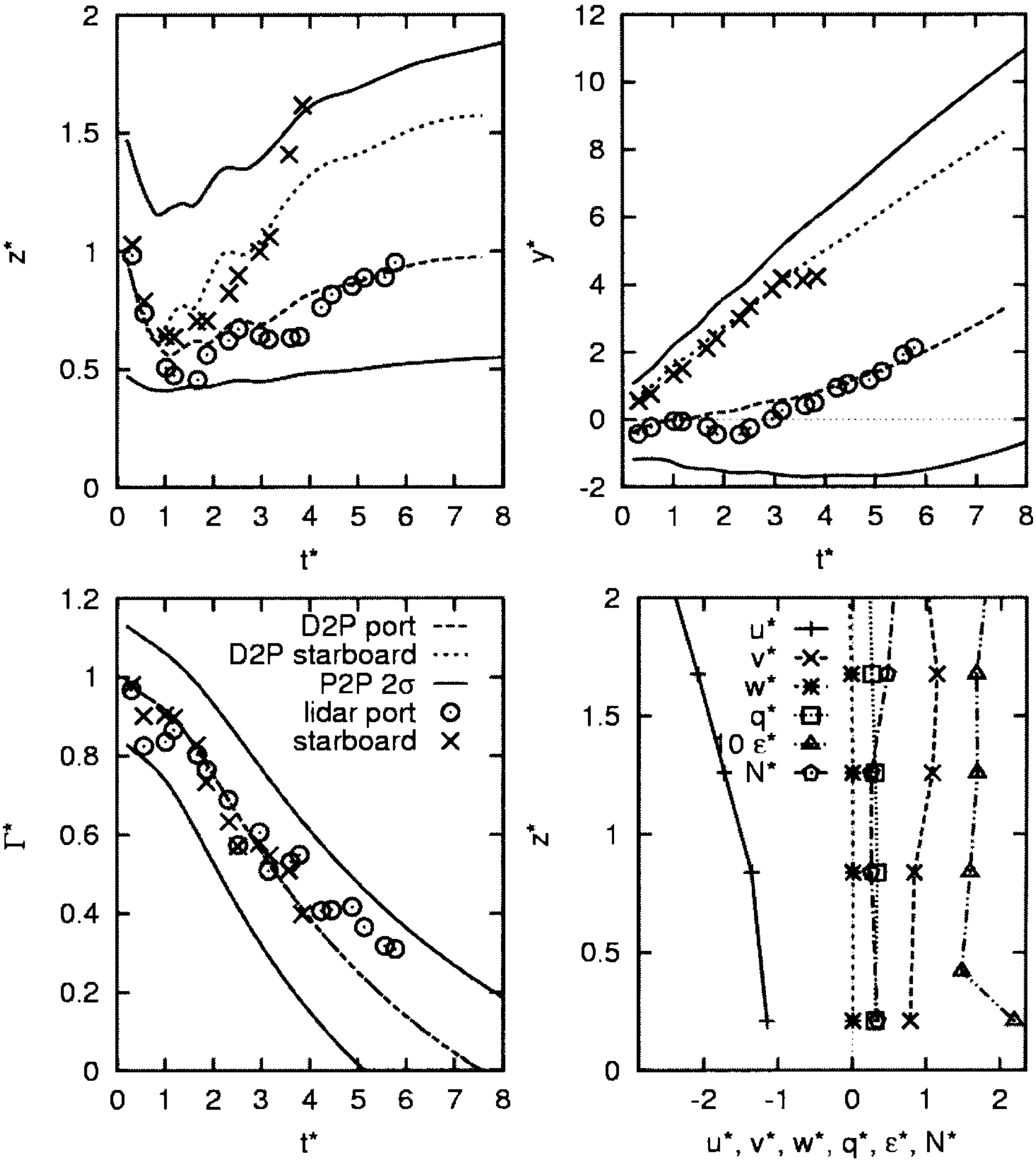

Figure 7. Evolution of normalized vertical (z*) and lateral positions (y*) and circulation (Γ*) in ground proximity. Measurements by lidar (symbols) and predictions with P2P wake vortex model (lines). Dashed and dotted lines denote deterministic behavior, solid lines are probabilistic envelopes (95.4%). The bottom right panel shows vertical profiles of measured meteorological parameters. Normalizations are based on initial values of vortex spacing, circulation, and the time needed to descend one vortex spacing.

For the time being, the confidence intervals for y, z, and Γ are adjusted to 2σ-probabilities. The respective uncertainty allowances are achieved by a training procedure that employs statistics of measured and predicted wake vortex behavior [Holzäpfel, 2006]. Note that the training procedure implicitly considers the quality of the meteorological input data. As a consequence, uncertainty allowances of wake-vortex predictions based on the high-quality SODAR/RASS measurements in the lowest three gates are smaller than uncertainty allowances applied to wake-predictions at higher altitudes, which are based on NOWVIV input.

Safety-Area Prediction

Once the potential positions of the wake vortices at each gate are known, safe distances between wake vortex core positions and the follower aircraft need to be assigned. The Simplified Hazard Area (SHA) concept [Hahn et al., 2004; Schwarz and Hahn, 2006] predicts distances that allow for safe and undisturbed operations.

The SHA-concept assumes that for encounters during approach and landing the vortex induced rolling moment constitutes the dominant effect [de Bruin, 2003; Hallock and Eberle, 1977; Schwarz and Hahn, 2006] and can be used to define a safety area representing the entire aircraft reaction. Then encounter severity can be characterized by a single parameter, the required Roll Control Ratio RCR_{req}, which relates the roll control input that is required to compensate the exerted rolling moment to the maximum available roll control power.

In Figure 8 the innermost areas with $RCR_{req} > 1$ denote regions where the roll capability of the follower aircraft is exceeded. Full flight simulator investigations yield acceptable results for manual control at a value of $RCR_{req} = 0.2$ [Schwarz and Hahn, 2006]. Results from real flight tests using DLR's fly-by-wire in-flight simulator, ATTAS, support this conclusion [Schwarz and Hahn, 2005]. In Figure 8 the lines a and b denote the resulting distances between vortex centers and follower aircraft for $RCR_{req} < 0.2$, which are added to the wake vortex envelopes.

As for wake vortex prediction, no individual wake vortex and follower aircraft pairings are considered for the WSVBS (although that would be possible) but wake vortex envelopes that represent the heavy category are combined with the follower categories medium or heavy. In order to conservatively represent these follower aircraft weight classes, all relevant aircraft parameters (wing span, wing area, airspeed, lift coefficient, maximum roll control power, and taper ratio) are conservatively combined to mimic the worst case scenarios. The values of the worst case parameter combinations are again derived from envelopes of aircraft parameters as a function of MTOW, as described in the section on Representation of Aircraft

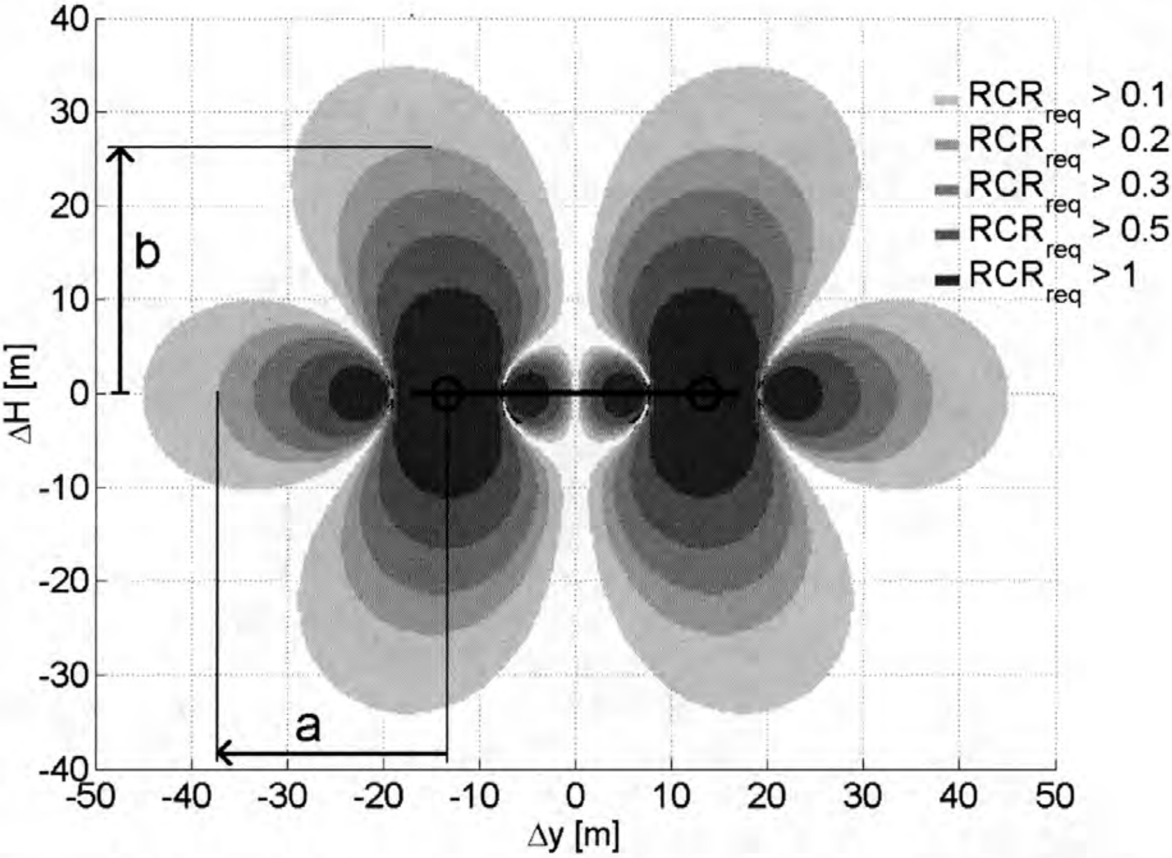

Figure 8. Roll control power required to compensate wake-vortex induced rolling moments. Horizontal and vertical allowances a and b for $RCR_{req} < 0.2$.

Weight Classes for wake vortex prediction. This method of using MTOW-based aircraft parameters for the determination of simplified hazard areas is called SHAPe (Simplified Hazard Area Prediction) [Hahn et al., 2004].

SYSTEMS INTEGRATION

This section describes how the above introduced components are combined for the prediction of adapted aircraft separations. The first part considers components within a single gate. The second part then explains how the minimum temporal aircraft separations are derived from the predictions within all the gates. Finally, the third part sketches the temporal prediction cycle, which defines parameters such as update rate and prediction horizon.

Components in Single Gate

Figure 5 illustrates the process seen in flight direction in control gate 11 for the leader aircraft parameter combination Γ_{0uu}, b_{0uu} and a vortex age of 100 s. The different ellipses are defined by the respective sums of vertical and horizontal probabilistic allowances of the components approach corridor, the vortex area prediction, and the safety area prediction. Note that horizontal and vertical dimensions in Figure 5 are in scale.

The corridor of possible vortex positions (vortex area) indicates that superimposed with vortex descent a southerly cross-wind advects the wake from runway 25L to 25R. Because the lateral vortex positions are predicted less precisely (uncertainty and variability of crosswind) than vertical position (cf. Figure 4), the aspect ratio of the vortex area ellipse exceeds a value of eight. Out of ground effect where uncertainties regarding vortex descent are increased [Holzäpfel and Steen, 2007] this aspect ratio is much smaller. Safety area margins for aircraft pairings HH and HM are added to the vortex corridors, resulting in overall safety areas to be avoided. One important aspect is that the safety corridors are not static. Rather, they move depending on wake transport, grow due to vortex spreading, and shrink according to wake decay.

For aircraft pairings on approach to a single runway, the time interval between the passage of the generator aircraft through a gate and the time when a safety area no longer overlaps the approach corridor (gate obstruction time) determines the minimum temporal separation for that gate. However, for the parallel runway system, the question is whether the safety areas reach the neighboring runway within the prediction horizons. The prediction horizons of 100 s for HH and of 125 s for HM are derived from the temporal equivalents to ICAO separations used by the DLR Arrival Manager (AMAN).

The example in Figure 5 illustrates that after 100 s the vortex area has just left the approach corridor of runway 25L, yet the gate is blocked as both safety corridors still overlap with the approach corridor. On the other hand, after 100 s the safety envelopes for HH and HM have not reached the glide path corridor for 25R. However, at 125 s the HM envelope will reach the glide path corridor for 25R. Therefore, reduced separations for 25R can only be assigned to heavy aircraft. Safety areas from 25R in turn will not reach the corridor 25L, so for aircraft approaching 25L reduced separations can be applied to both follower weight categories.

Complete Domain

One prediction sequence comprises 13 gates for each runway, 8 generator aircraft parameter combinations, 3 runway combinations (generator and follower on single runway (25L25L or 25R25R), generator on 25L and follower on 25R (25L25R), and vice versa), and 2 follower weight classes. So, in total 1248 cases are considered. From the 1248 cases for each of the 3 runway combinations and 2 follower weight classes the cases with maximum vortex ages and potential wake encounter conflicts are identified. These maximum

Table 3. Minimum Separation Times for Different Runway and Weight Category Combinations

rwy comb.	MST HH [s]	MST HM [s]
25L25L	100	125
25L25R	0	125
25R25L	0	0
25R25R	100	125

gate obstruction times define minimum aircraft separation times MST. The output of the WSVBS consequently consists of the matrix shown in Table 3.

Note that the MST in Table 3 are consistent with the situation displayed in Figure 5. In the matrix a MST = 0 s means that no aircraft separation with regard to wake vortices is needed, i.e. vortices do not reach the adjacent runway. In practice the aircraft separations can then be reduced to radar separation (for example 70 s). The translation of the separation matrix into procedures and displays that are suitable for air traffic control (ATC) is described in Part II of this paper.

The idea is that all corridors used in the process, such as those depicted in Figure 5, should be based on identical probability levels, currently, twice the standard deviations (2σ) of respective data. However, the safety area prediction concept is not probabilistic, i.e. the predicted safety areas are safe without any exception for the investigations conducted so far. It however, assumes that the wake vortices are situated along the envelopes of the vortex area, which is a very conservative assumption. A 2σ probabilistic confidence level on the safety module may be introduced by adding the safety areas only to 95.4% of the 2σ wake vortex areas. With this effective reduction of the vortex areas to 1.7σ (91.1%) a consistent probabilistic level of 95.4% is also achieved for the safety area module.

Unfortunately, the very question: “What overall safety is actually achieved by the combination of the various conservative elements of the WSVBS?” can not be answered easily. It is planned to adjust all components to consistent confidence levels once the methodology of a comprehensive risk analysis is established. This analysis will also have to consider risks occurring outside the area controlled by the WSVBS.

Prediction Cycle

Every 10 minutes new Sodar/RASS and NOWVIV data are available. After receipt of these data the WSVBS predicts MST matrices for a 60 min horizon with 10 min-increments. This guarantees availability of predictions for at least 45 min in advance as required by ATC for planning purposes.

WAKE-VORTEX MONITORING

Wake-vortex monitoring is used to identify potential erroneous predictions of the WSVBS. For this purpose DLR's 2 μm pulsed Doppler LIDAR is operated in vertical scan mode with elevations between 0° to 6° to detect and track the vortices alternately in the three lowest and most critical gates of runway 25R (see Part II of this paper). Once the real-time capability of vortex monitoring is established, it would be possible to integrate a conflict detection module, which may issue warnings and/or may adapt the WSVBS predictions.

CONCLUSIONS

This manuscript describes the design of the Wake Vortex Prediction and Monitoring System WSVBS with all its components and their interaction. The WSVBS consists of components that consider meteorological conditions, aircraft glide path adherence, multiple aircraft parameter combinations characterizing various aircraft weight categories, the resulting wake-vortex behavior, the surrounding safety areas, and wake vortex monitoring. The elements of the WSVBS are generic and can be adjusted to other runway systems and airport locations.

A specific feature of the WSVBS is the usage of both measured and predicted meteorological quantities as input to wake vortex prediction. In ground proximity where the probability of encountering wake vortices is highest, the wake predictor employs measured environmental parameters that yield superior prediction results. For the less critical aloft portions of the approach, which cannot be monitored completely by instrumentation, the meteorological parameters are taken from dedicated numerical terminal weather predictions. The P2P wake vortex model predicts envelopes for vortex position and strength that implicitly consider the quality of the meteorological input data. This feature is achieved by a training procedure that employs statistics of measured and predicted meteorological parameters and the resulting wake vortex behavior.

The WSVBS combines various conservative elements that presumably lead to a very high overall safety level of the WSVBS. a) Wake vortex prediction as well as safety area prediction employ worst case combinations of aircraft parameters that span complete aircraft weight categories. b) The wake vortex model assumes that the aircraft are situated at the limits of the approach corridor envelopes. (The probability that this assumption actually occurs is extremely small.) Likewise, the safety area model assumes that the wake vortices are situated at the limits of the wake vortex envelopes. As a consequence the probability to actually encounter wake vortices at the edges of the safety areas is extremely small. c) The most critical cases within the 1248 investigated parameter combinations determine the possible aircraft separations. d) A LIDAR scans the most critical gates at low altitude in order to verify the correctness of the suggested aircraft separations. The combination of these conservative measures leads to a very high but currently not quantified overall safety level. Once the methodology for a comprehensive risk analysis is established, it is planned to adjust all components to appropriate and consistent confidence levels.

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ACRONYMS

AMDAR	Aircraft Meteorological Data Relay
AMAN	Arrival Manager
ATC	Air Traffic Control
ATTAS	Advanced Technologies Testing Aircraft System
AVOSS	Aircraft Vortex Spacing System
AWIATOR	Aircraft Wing with Advanced Technology Operation
CSPR	Closely-Spaced Parallel Runways
DFS	Deutsche Flugsicherung GmbH
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DWD	Deutscher Wetterdienst
EDR	Eddy Dissipation Rate
FAF	Final Approach Fix
FLIP	Flight Performance Using Frankfurt ILS
HH	Heavy Followed by Heavy
HM	Heavy Followed by Medium
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
LIDAR	Light Detection and Ranging
LM	Local Model
MST	Minimum Aircraft Separation Time

NASA	National Aeronautics and Space Administration
NOWVIV	Nowcasting Wake Vortex Impact Variables
MM5	Mesoscale Meteorology Model 5
MLW	Maximum Landing Weight
MTOW	Maximum Take-Off Weight
P2P	Probabilistic Two-Phase Wake Vortex Model
RASS	Radio Acoustic Sounding System
RCR	Roll Control Ratio
SHA	Simplified Hazard Area Concept
SHAPe	Simplified Hazard Area Prediction
SODAR	Sound Detection and Ranging
TDZ	Touchdown Zone
USA	Ultra Sonic Anemometer
UTC	Universal Time Coordinated
WSVBS	Wake Vortex Prediction and Monitoring System
WTR	Wind Temperature Radar
WVWS	Wake Vortex Warning System

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